Numerical Evaluation of Stress Intensity Factors

J-Integral Approach

by

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Outline

- Problem Description
- Objectives
- Fracture mechanics & Finite Elements
- J-Integral Formulation
- Numerical Solution of semi Infinite Plate with Edge crack
- 3D Finite Element Analysis of Miter Gate with Multiple Cracks
- Miter Gate Experimental Evaluation
- Conclusions

Problem Description (1/2)

- Gates significant number of lockage & repeated loading
- Unsatisfactory performance
  - Fatigue cracking due welded connections
  - Poor welding quality
  - Unanticipated structural behavior or loading

Problem Description (2/2)

- Failures of diagonals on miter gates.
  - These appear to be fatigue-induced failures driven by the connection details
  - Current design guidance results in a much larger prestress than may be required
- Stress Intensity Factor (SIF) hand calculations are long and tedious
- Maintenance and repair of f&f failures are a majo e

Objectives (1/2)

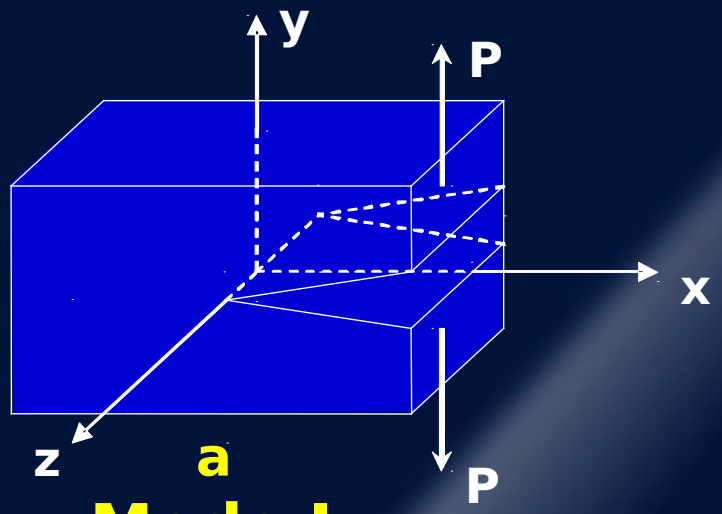
- To develop Analytical techniques for employing state-of-the-art capabilities for fracture mechanics analysis using finite element modeling
  - 3D finite element analysis of gates
  - commercially available nonlinear finite element programs
  - J-integral analysis for fracture analysis
    - Directly compared to elastic or elastic-plastic material properties for assessment

Objectives (2/2)

- Validate model with experimental data
- Assess the connection detailing and design of miter gate diagonals
  - development of analytical models to assess the prestress requirements
  - develop improved details for diagonal/gate connections

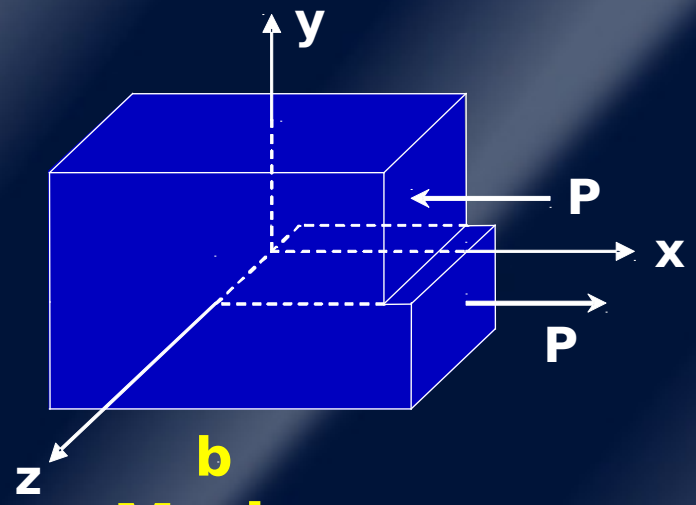
Fracture Mechanics and the Application to Finite Elements

Modes of Fracture



a

Mode I



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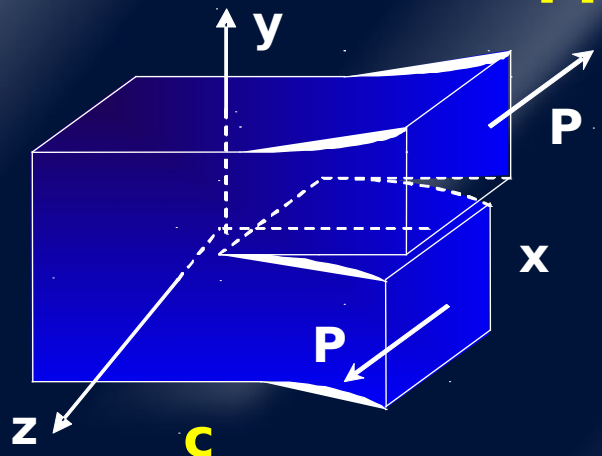
Mode II



c

Mode III

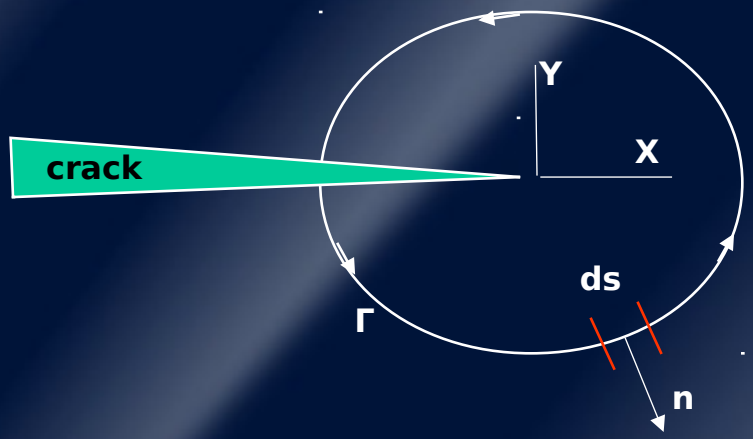
Implementation of Fracture Mechanics in Finite Elements

- Discrete Crack Model
  - Stress field magnitude & the stresses near a crack tip == loading applied , to the size, shape, and orientation of the crack.
  - If (K_I i.e., the demand) > (K_{IC} fracture toughness, i.e., the capacity) a crack propagates
    - K_I (SIF) -- rate o change in stress as the crack tip is approached
    - K_{ic} is considered a material property, ability to carry loads plastically in the presence of a crack.
    - Remeshed is required

J-Integral

J-Integral

- Consider a nonlinear elastic body containing a crack



$$J = \int_{\Gamma} w\partial y - T_i \frac{\partial u_i}{\partial x} \partial s$$

$$w = \int_0^{\varepsilon_{ij}} \sigma_{ij} \partial \varepsilon_{ij}$$ **Strain energy**

$$T_i = \sigma_{ij} n_j$$ **Traction vector**

Γ arbitrary contour around crack tip
n is the unit vector normal to Γ

J-Integral

- Rice, J. R., 1968, showed that the J integral is a *path-independent* line integral and it represents the *strain energy release rate of nonlinear elastic materials*

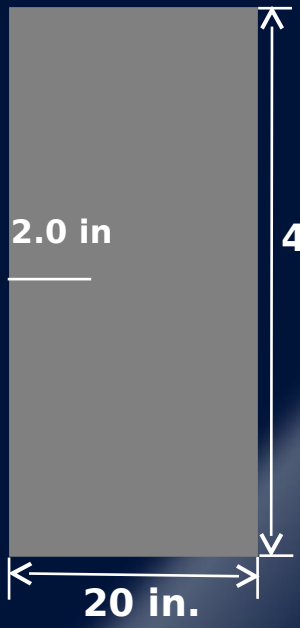
$$J = \frac{\partial \Pi}{\partial A}$$

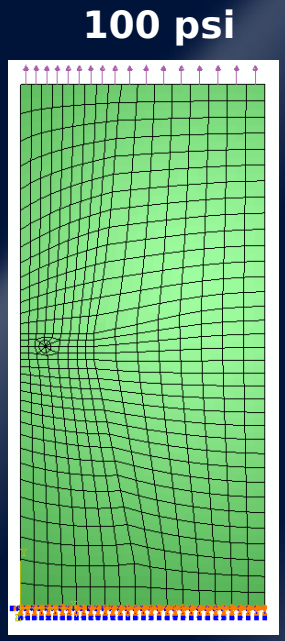
- For LE material J is the strain energy release rate G

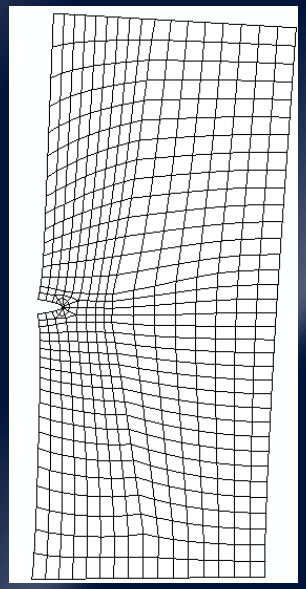
$$J = G = \frac{K^2}{[E]}$$

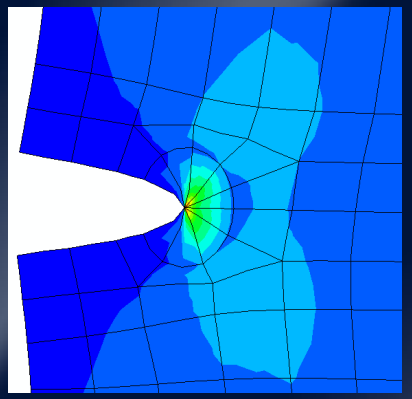
Numerical Solution of Infinite Plate with Edge crack

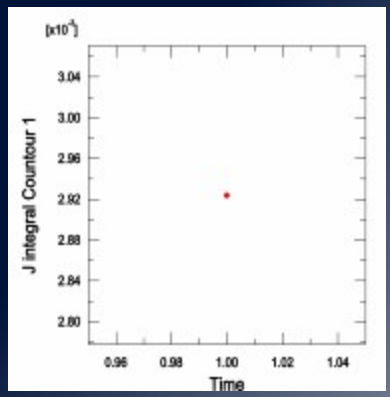
Numerical Solution of Infinite Plate with Edge crack











$$J = \frac{K^2}{E}$$

$$K = \sqrt{JE}$$

$$K = 2965 psi\sqrt{in}$$

$$K = 1.12\sigma\sqrt{\pi a} * k(a/b)$$

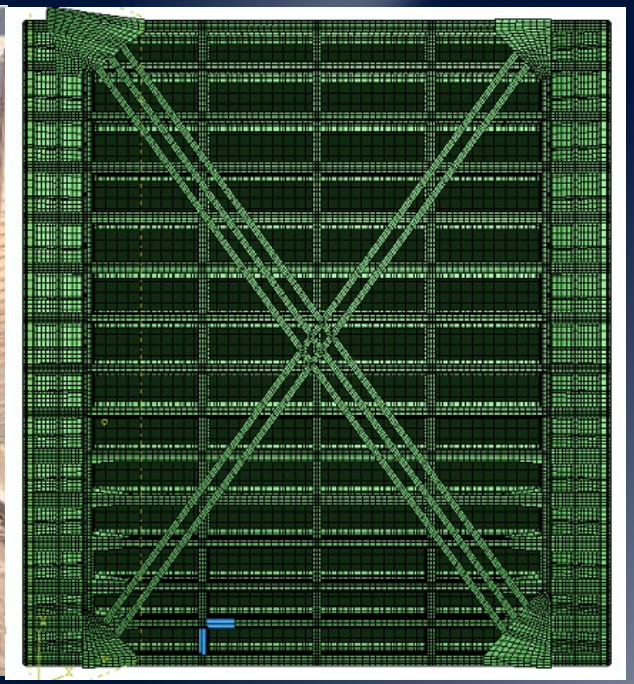
$$K = 1.12 * 100 * \sqrt{\pi * 2} * 1.07$$

$$K = 300 psi\sqrt{in}$$

3D Finite Element Analysis of Miter Gate with Multiple Cracks

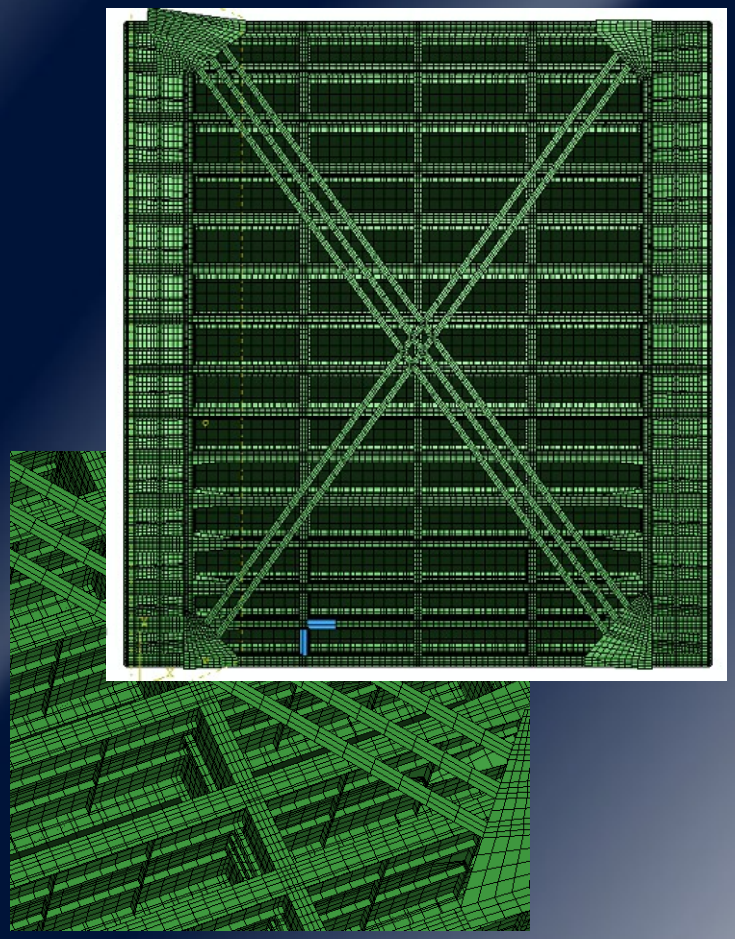
3D Finite Element Analysis of Miter Gate with Multiple Cracks

- 3D CAD Drawing As Build Structure
- Trimmed Surfaces Generation
- Import into FEM Application
- Generate 3D FEM Mesh



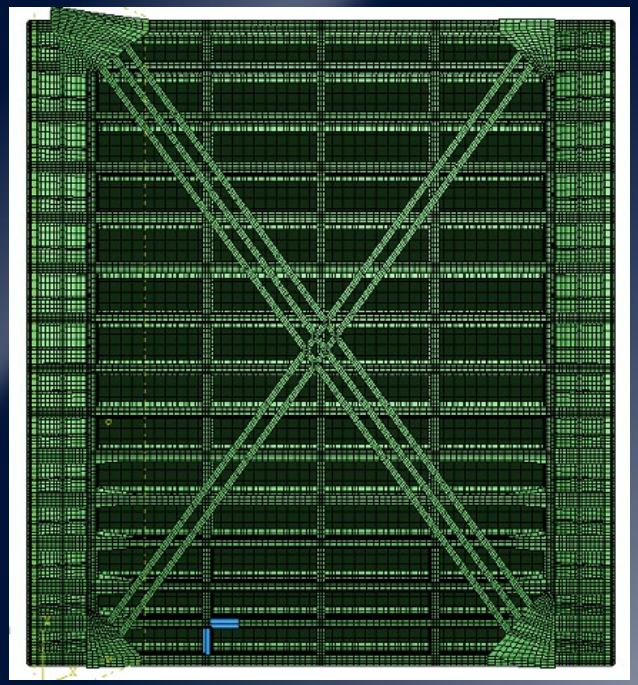
3D Finite Element Analysis of Miter Gate with Multiple Cracks

- Actual details are well represented
- No need to simplify details
- Boundary conditions are easily apply
- Possibility to study welded connection with special interface elements



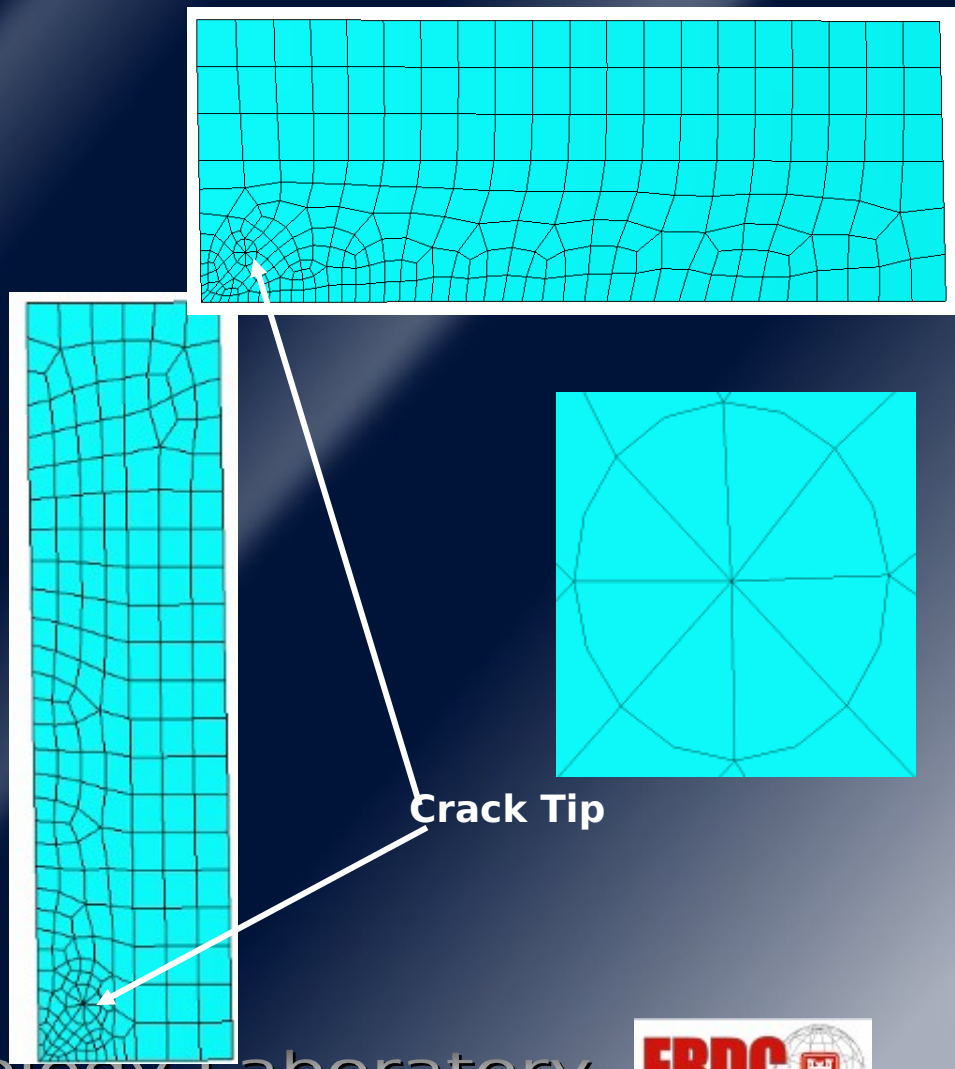
3D Finite Element Analysis of Miter Gate with Multiple Cracks

- 364,734 nodes
- 123,193 shell elements
- S8R5 shell element
  - 8 nodes
  - 5 DOF /node



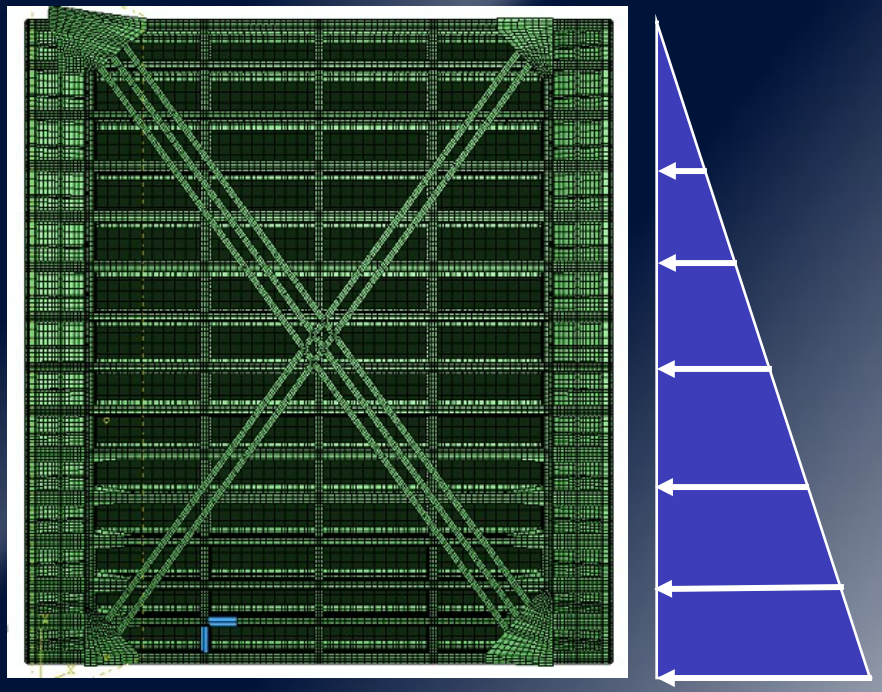
3D Finite Element Analysis of Miter Gate with Multiple Cracks

- Quarter Point triangular elements
- Singularity included to improved solution (singular strain field)
- Ring of quadratic triangular elements around the crack front



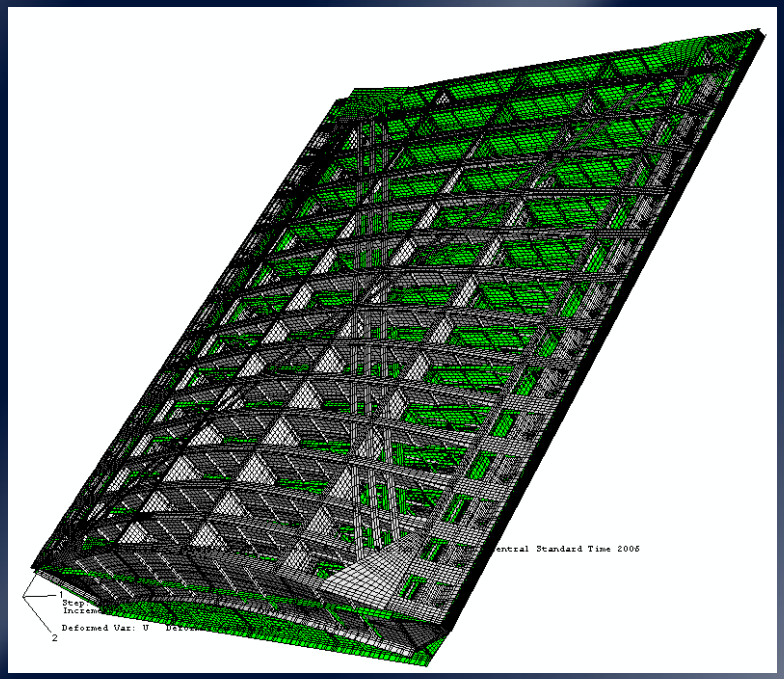
3D Finite Element Analysis of Miter Gate with Multiple Cracks

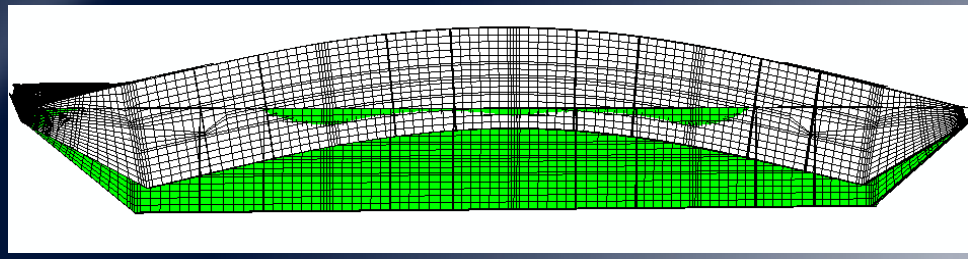
- Hydrostatic head of 61.5 ft.
- H=61.5 ft.
- W=61.5 ft.



3D Finite Element Analysis of Miter Gate with Multiple Cracks

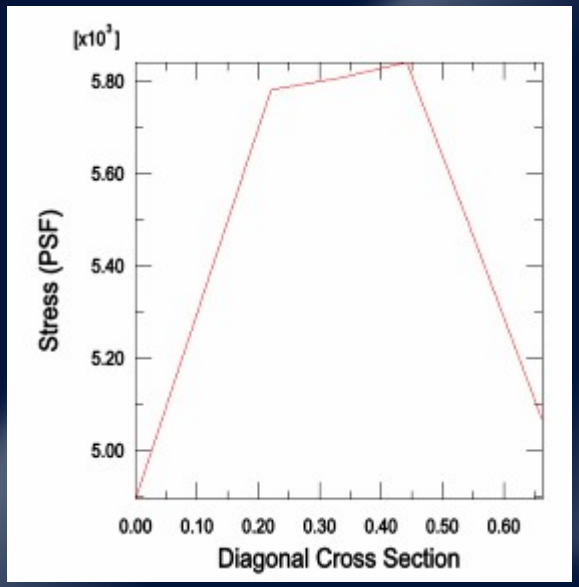
- Deformation
  - U1,U2, U3 = 0
    - Miter & Qouin
  - U3 = 0
    - Pintle
  - U1,U2 = 0
    - Gudgeon

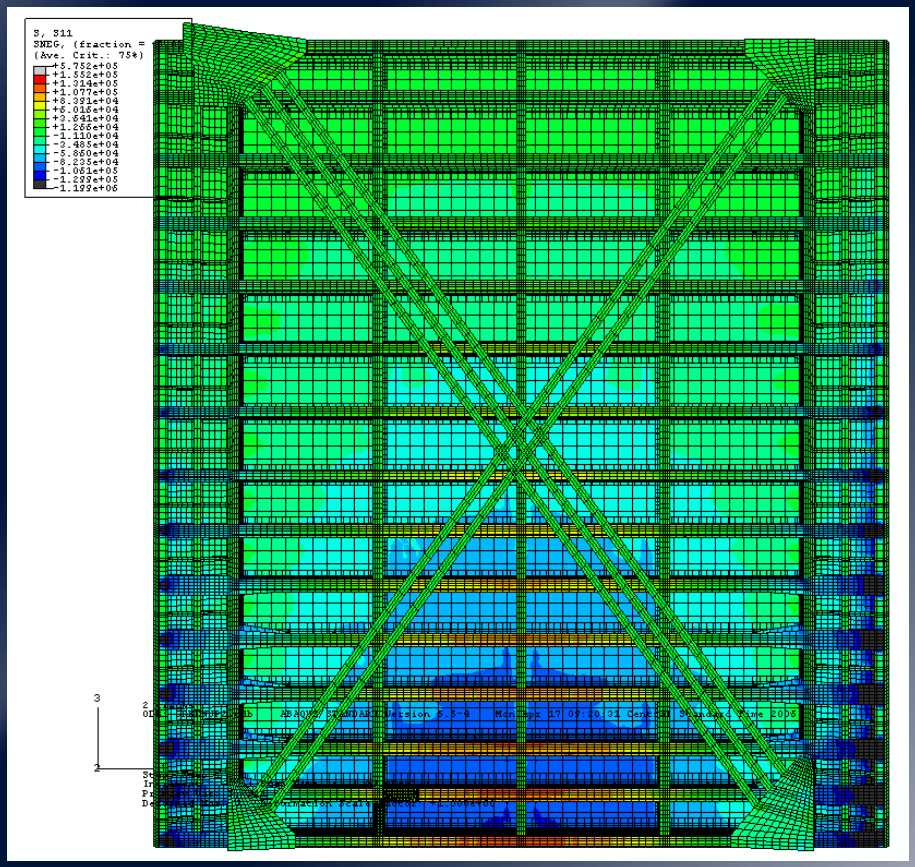




3D Finite Element Analysis of Miter Gate with Multiple Cracks

- Stress Contour





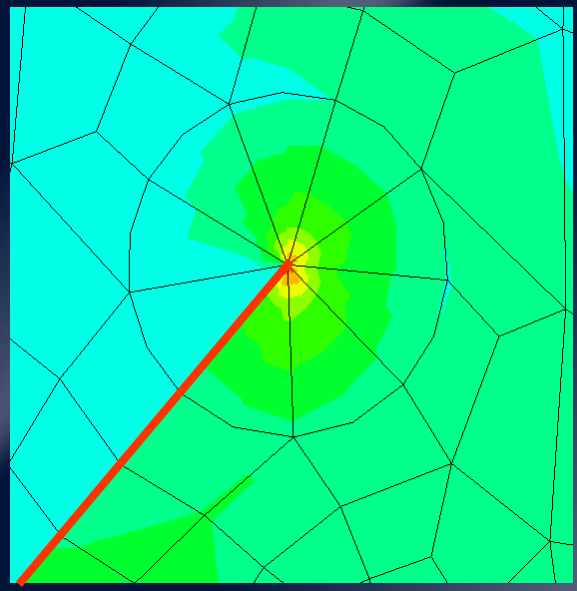
3D Finite Element Analysis of Miter Gate with Multiple Cracks

- σp1 = 1215 psi
- J = 82 psf*ft = 6.91 psi*in

$$J = \frac{K^2}{E}$$

$$K = \sqrt{JE}$$

$$K = 14{,}397 psi\sqrt{in}$$



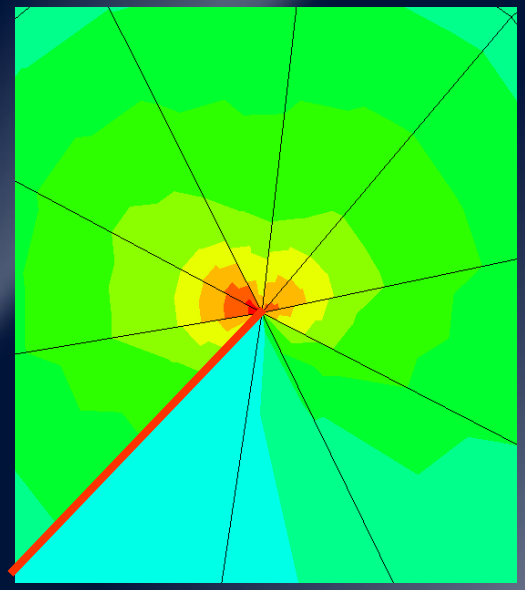
3D Finite Element Analysis of Miter Gate with Multiple Cracks

- σp1 = 3990 psi
- J = 296 psf*ft = 24.66 psi*in

$$J = \frac{K^2}{E}$$

$$K = \sqrt{JE}$$

$$K = 27{,}202 psi\sqrt{in}$$



Miter Gate Experimental Evaluation

- Dr. Padula, Mr. Barker, & Mr. Kish
- **An instrumentation to monitor behavior of girders and diaphragm around the pintle**
- **Short term objective was to verify behavior of bottom girders**

- **Long term objective was to monitor girders and diaphragm for changes in behavior over time as a result of shifting or misalignment of the gate, cracking or other damage**

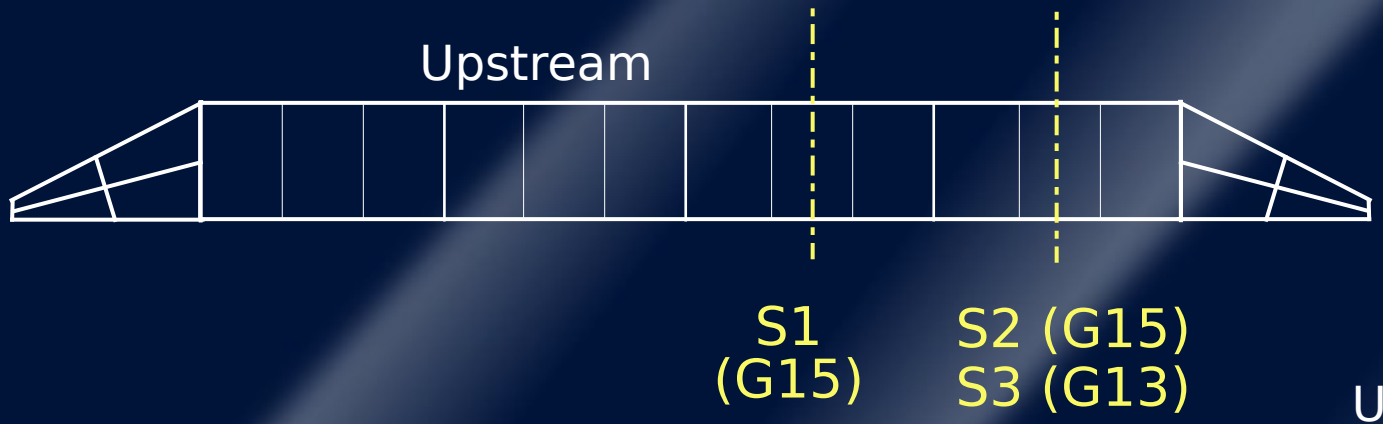
Miter Gate Experimental Evaluation

Strain Gage Locations

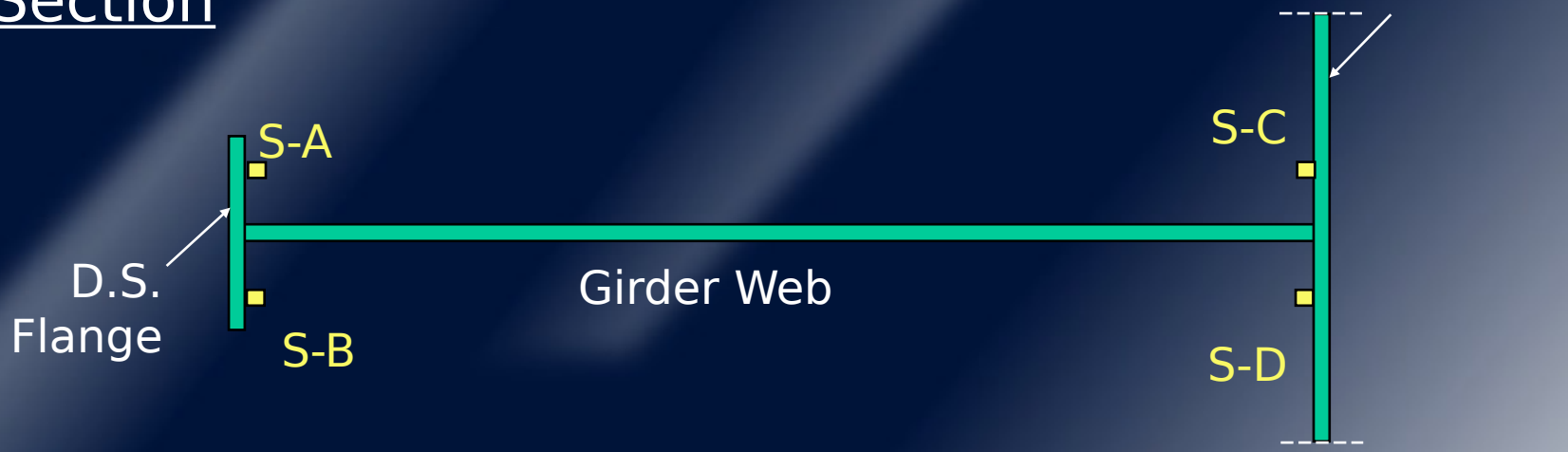
Gage Sets 1, 2, 3, and 5 were installed on horizontal flange of the G13, and G15 Girders

Gage Set 4 was installed on the vertical girder flange

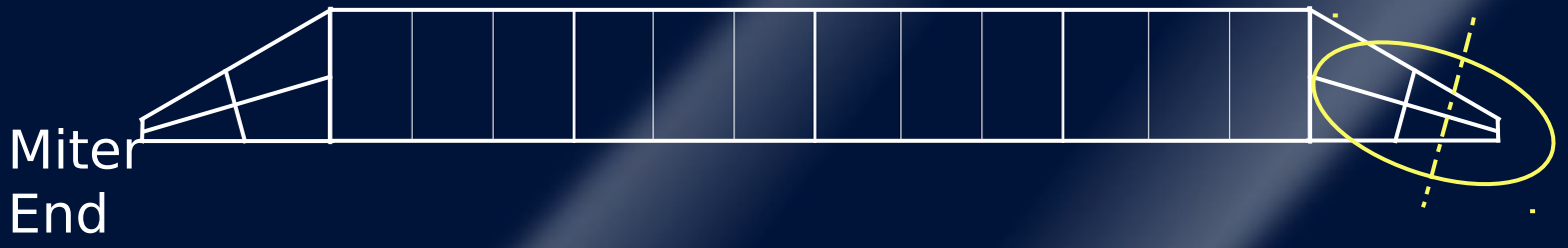
Miter Gate Experimental Evaluation

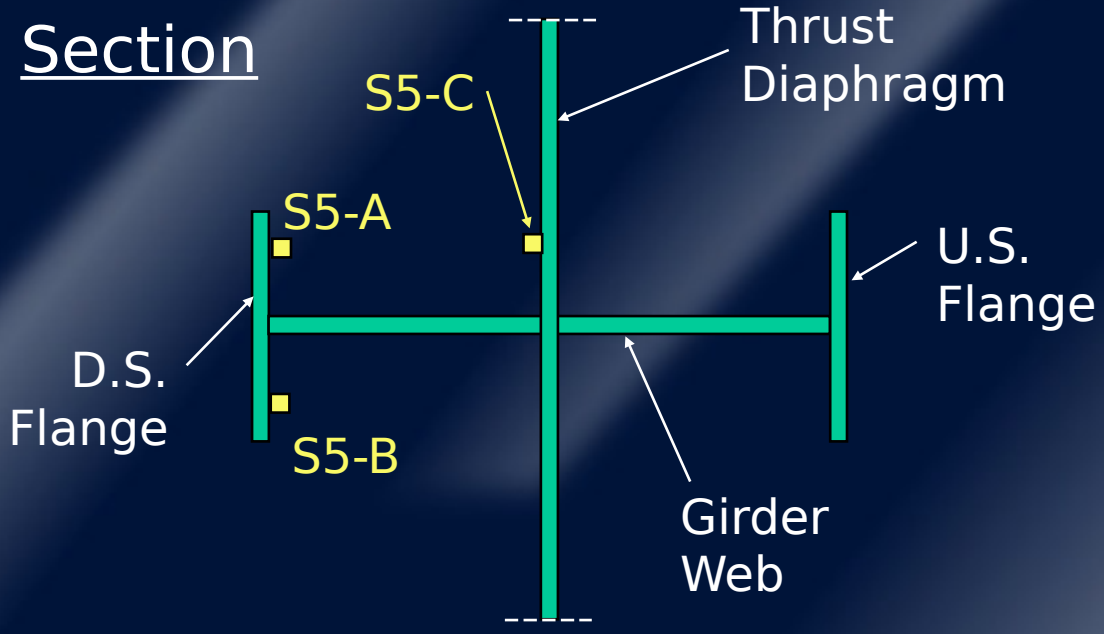


Section

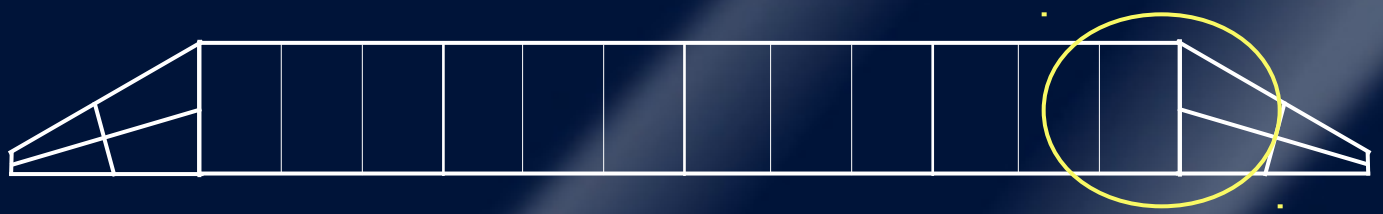


Miter Gate Experimental Evaluation



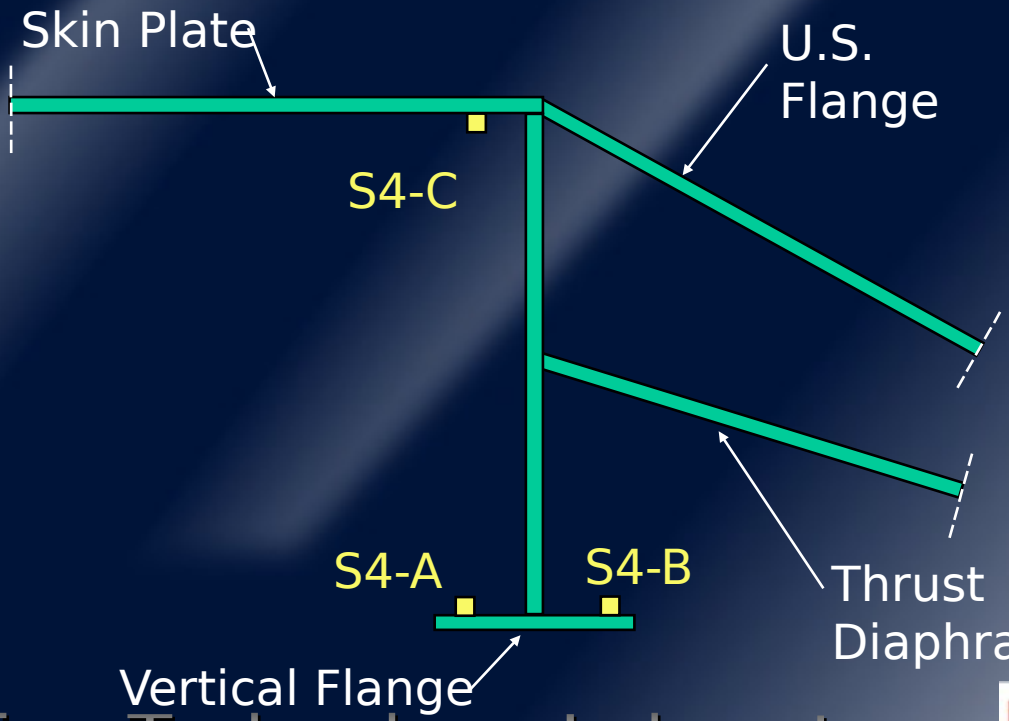


Miter Gate Experimental Evaluation



Miter End

Detail



Conclusions

- Analytical techniques using State of the Art capabilities
  - Linear Elastic Fracture Mechanics
  - J-integral
- 3D Finite Element Meshing Capabilities
  - CAD Drawing direct to FEM Program
- Successful prediction of stress intensity factors
  - Plate with Edge crack
  - 3D FEM of Miter Gate with multiple cracks
- Experimental data

Recommendations and Further Research

- Validation of 3D model
- Assess the connection detailing and design of miter gate diagonals
  - development of analytical models to assess the prestress requirements
  - develop improved details for diagonal/gate connections

Questions?